Three Dimensional Printing

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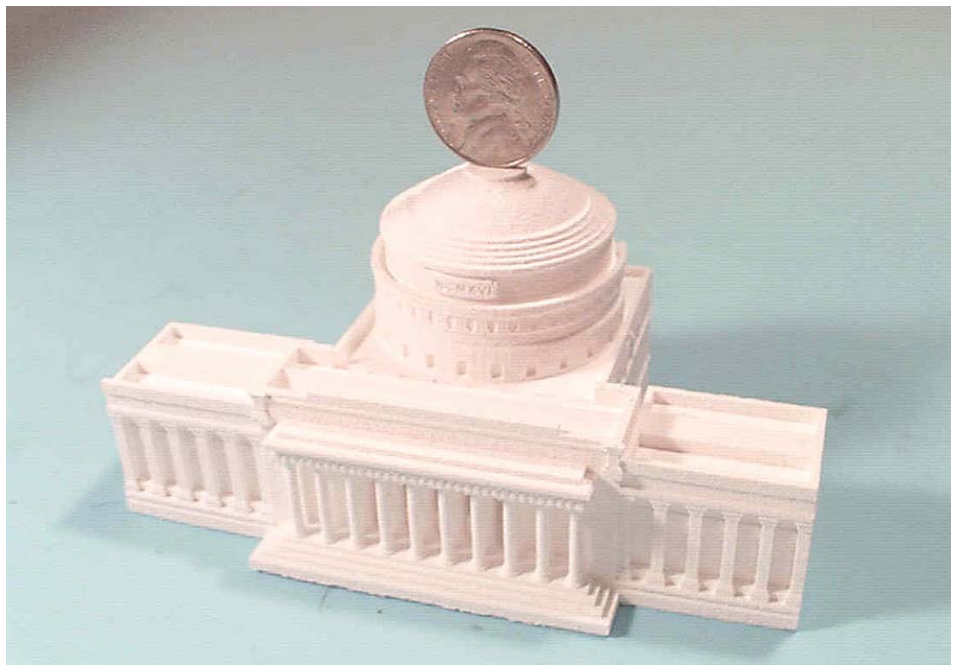

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14. ABSTRACT
3D Printing is an SFF Process which creates parts in layers. Each layer is formed by spreading powder and selectively joining the powder by ink-jet printing of a binder material.

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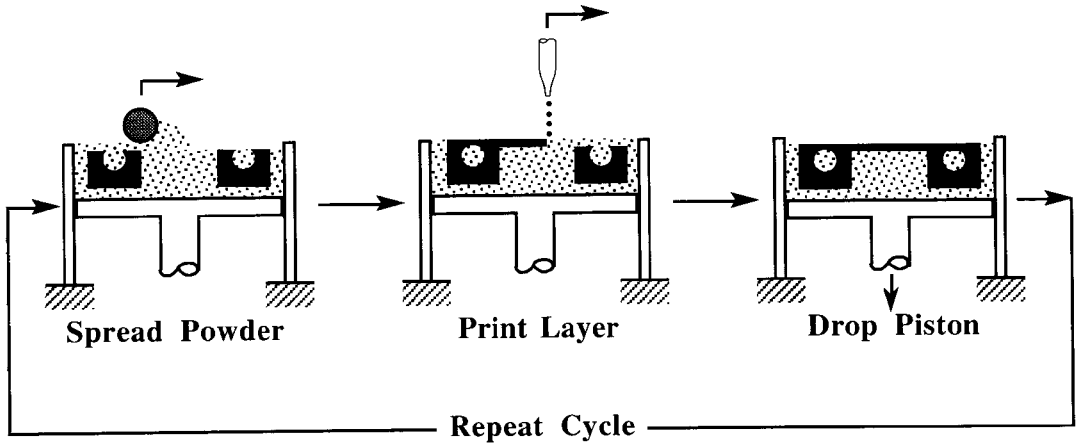
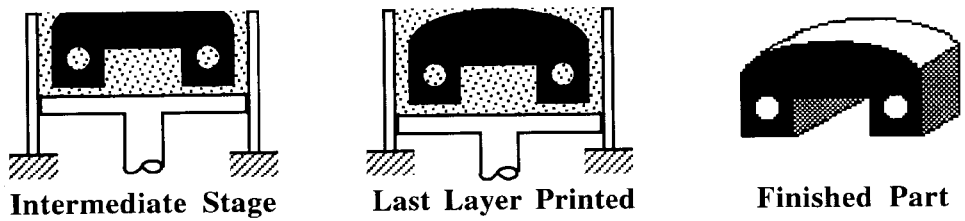
The 3D Printing Process

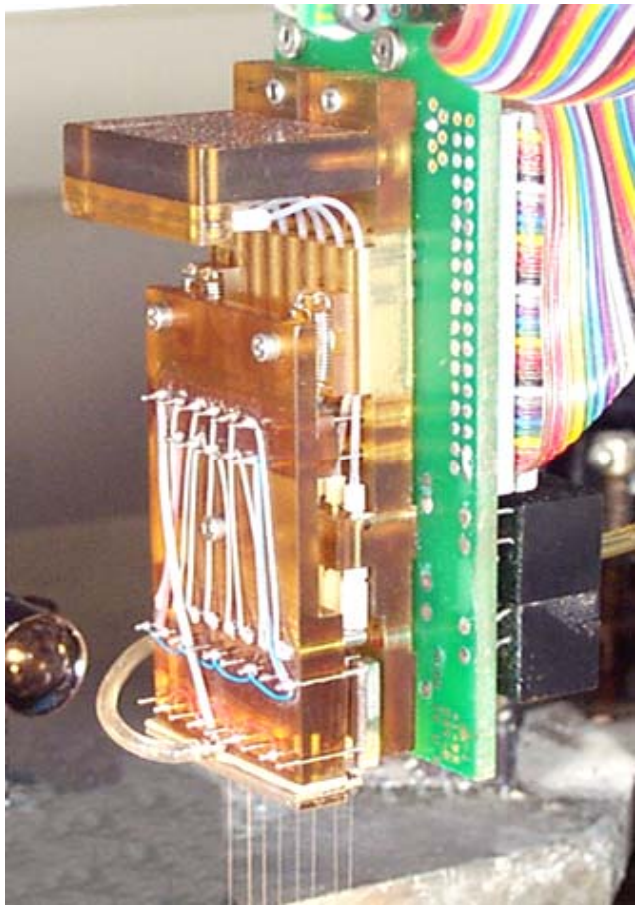


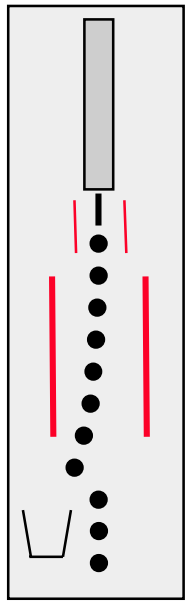


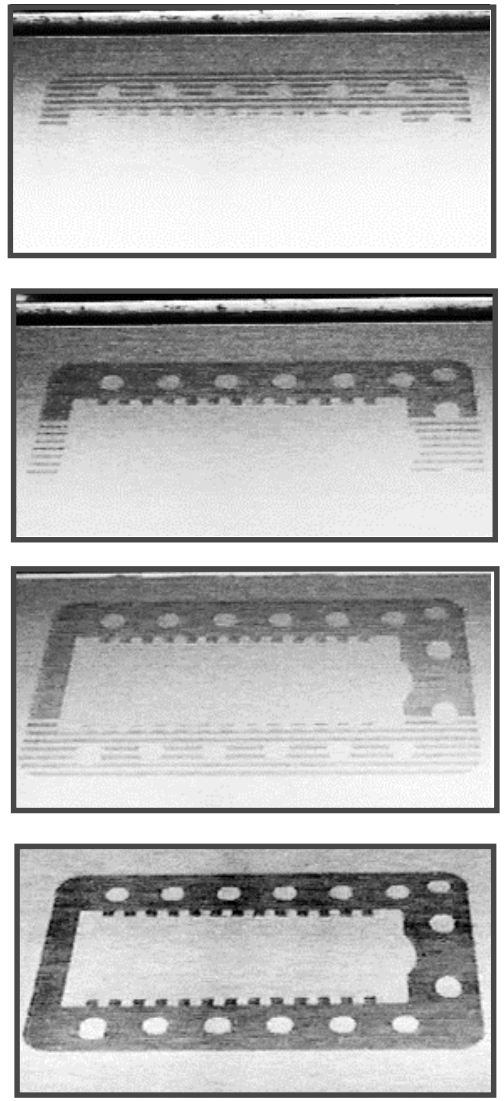
- **Any material as a powder**
- **Scaleable with multiple nozzles**
- **Local Composition Control**

3D Printing is an SFF Process which creates parts in layers. Each layer is formed by spreading powder and selectively joining the powder by ink-jet printing of a binder material.

MIT's 8-jet Printhead



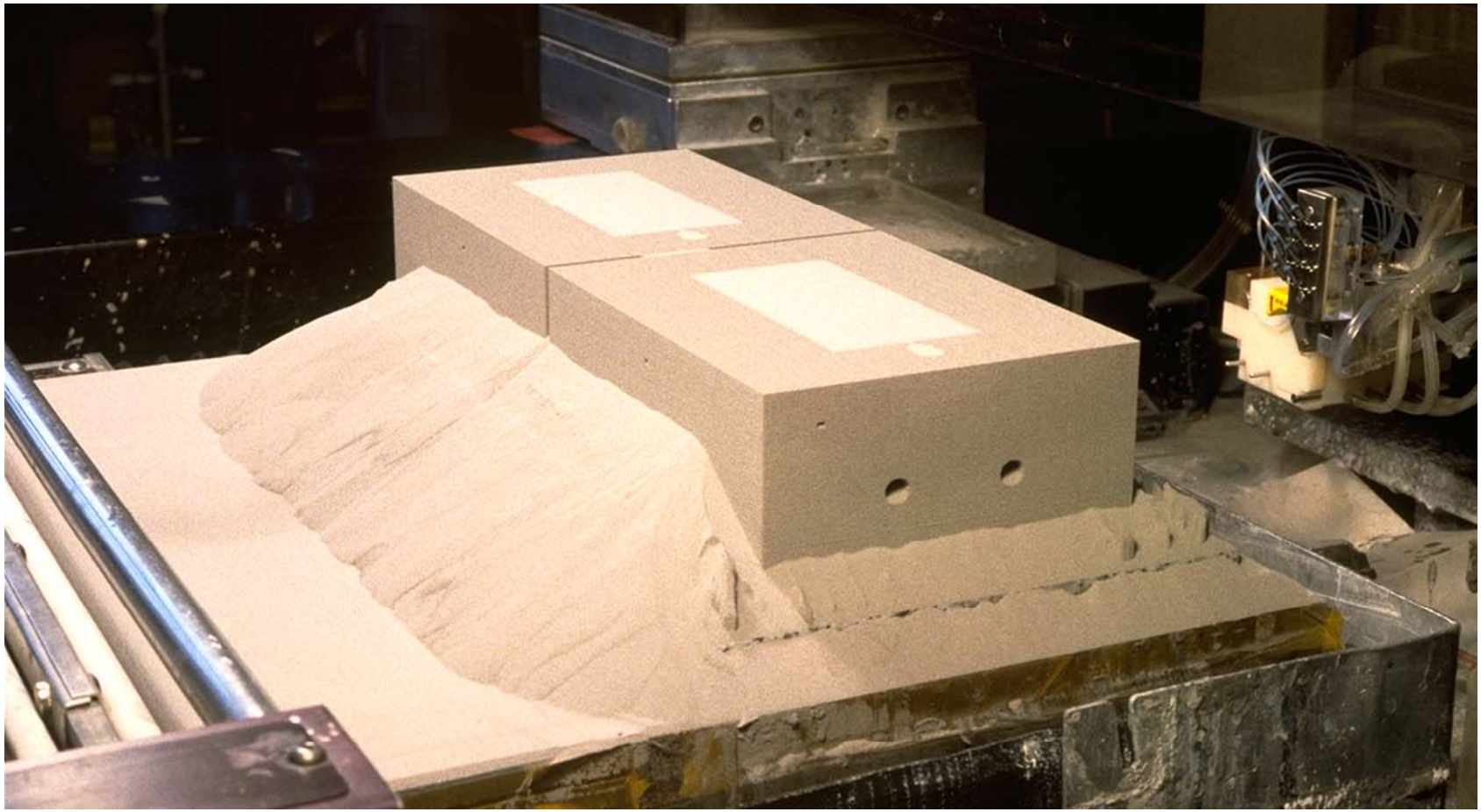




Allows for wide range of materials, precise droplet location and scalability.

Printing a layer

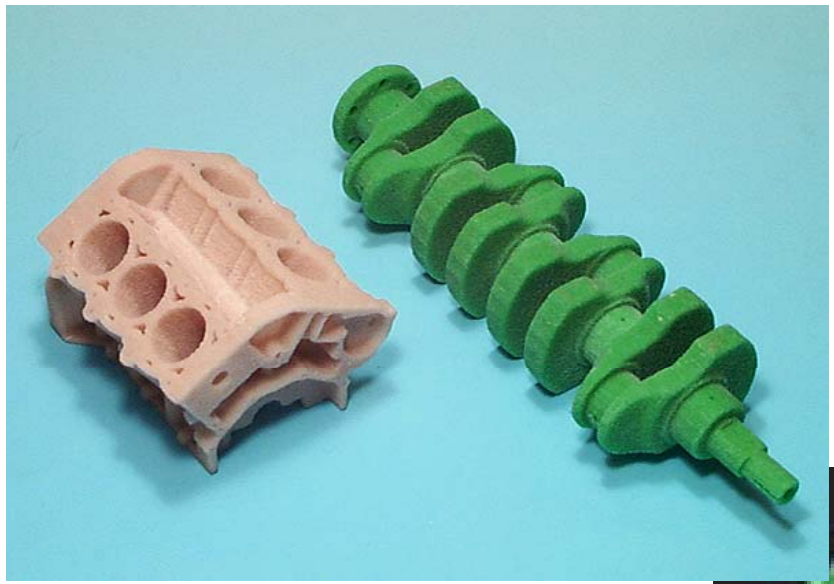
Removing the Green Part from the Powder Bed



Office Modeler;

Z Corp., Burlington, MA

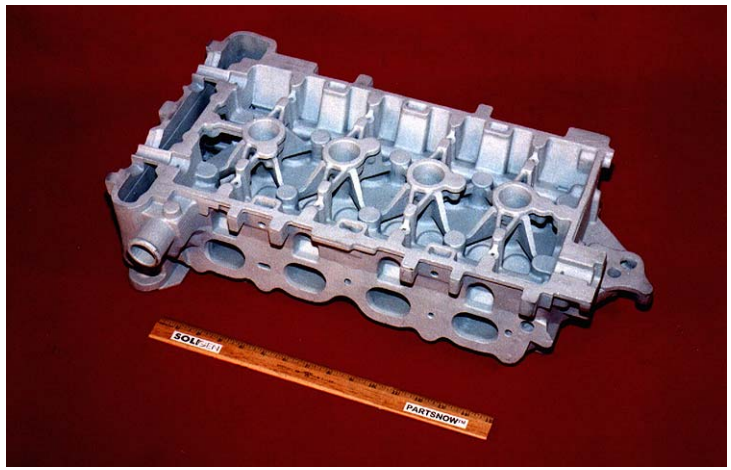
- **Low cost machine.**
- **Office environment (water binder, starch powder or plaster based)**
- **High reliability.**
- **FAST**

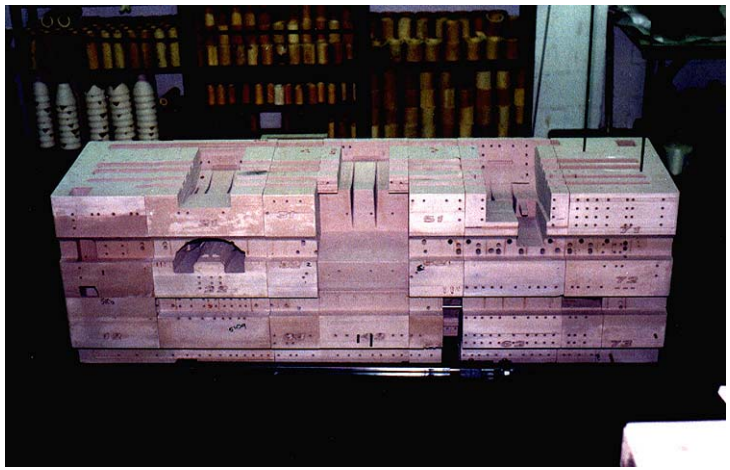


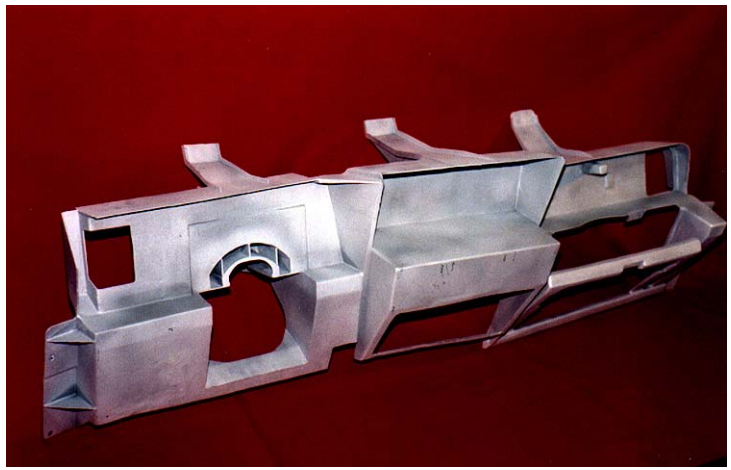
Ceramic Molds for Metal Castings;

Soligen, Inc. Northridge, CA

- 3D Print Ceramic mold
  - Colloidal silica binder into alumina powder
- Fastest route to a casting.
- Soligen Operates “Parts Now” which accepts files and returns castings.







Filters;

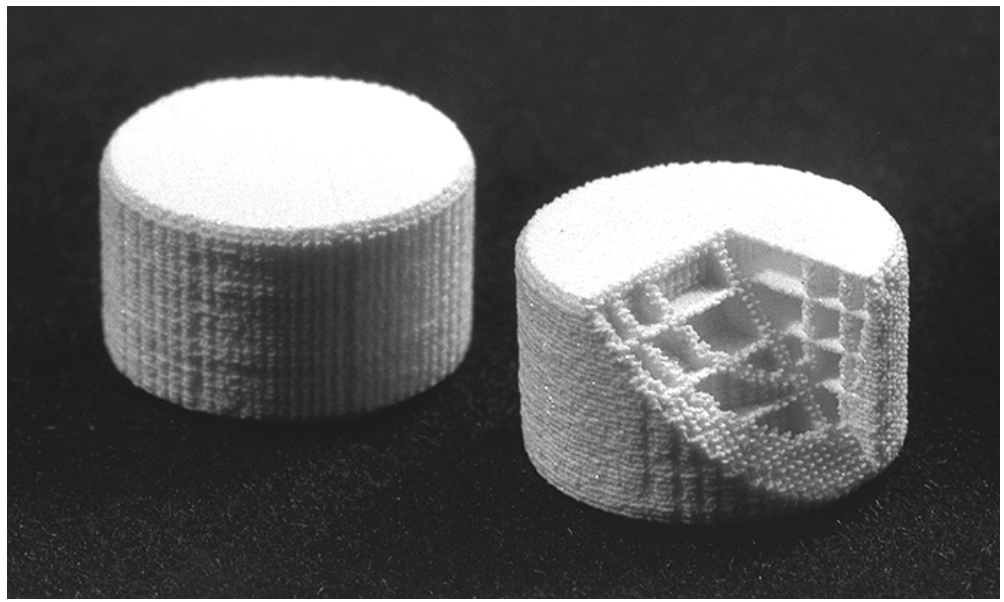
Specific Surfaces, Franklin, MA

- **Focus: ceramic filters for power plants - high filter area, durable, cleanable.**
- **Successful tests in “bag houses” (2000 hours). Tests on full scale pilot plant next. EPRI funded.**

Medical Applications;

Therics, Inc. Princeton, NJ

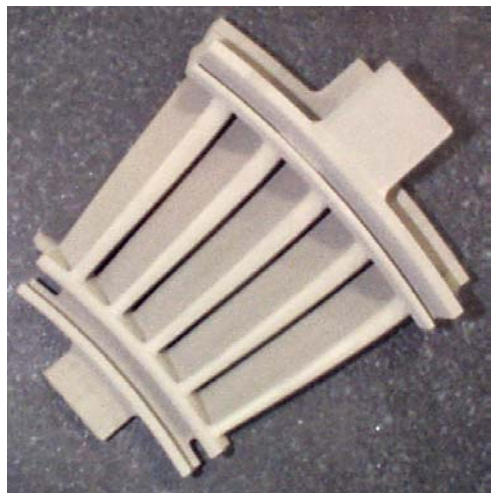
- **Drug delivery devices.**
- **Scaffolds for tissue engineering.**
- **Direct printing of tissue and organs.**
- **Direct printing of metallic prostheses.**



Direct Printing of Metal Tooling;

ExtrudeHone Corp., Irwin, PA

- **Directly print metal tooling.**
  - **Polymer binder into metal powder.**



Tooling by Direct Printing

- Colloidal latex binder
- Stainless steel or tool steel powder

→ Remove unprinted powder →

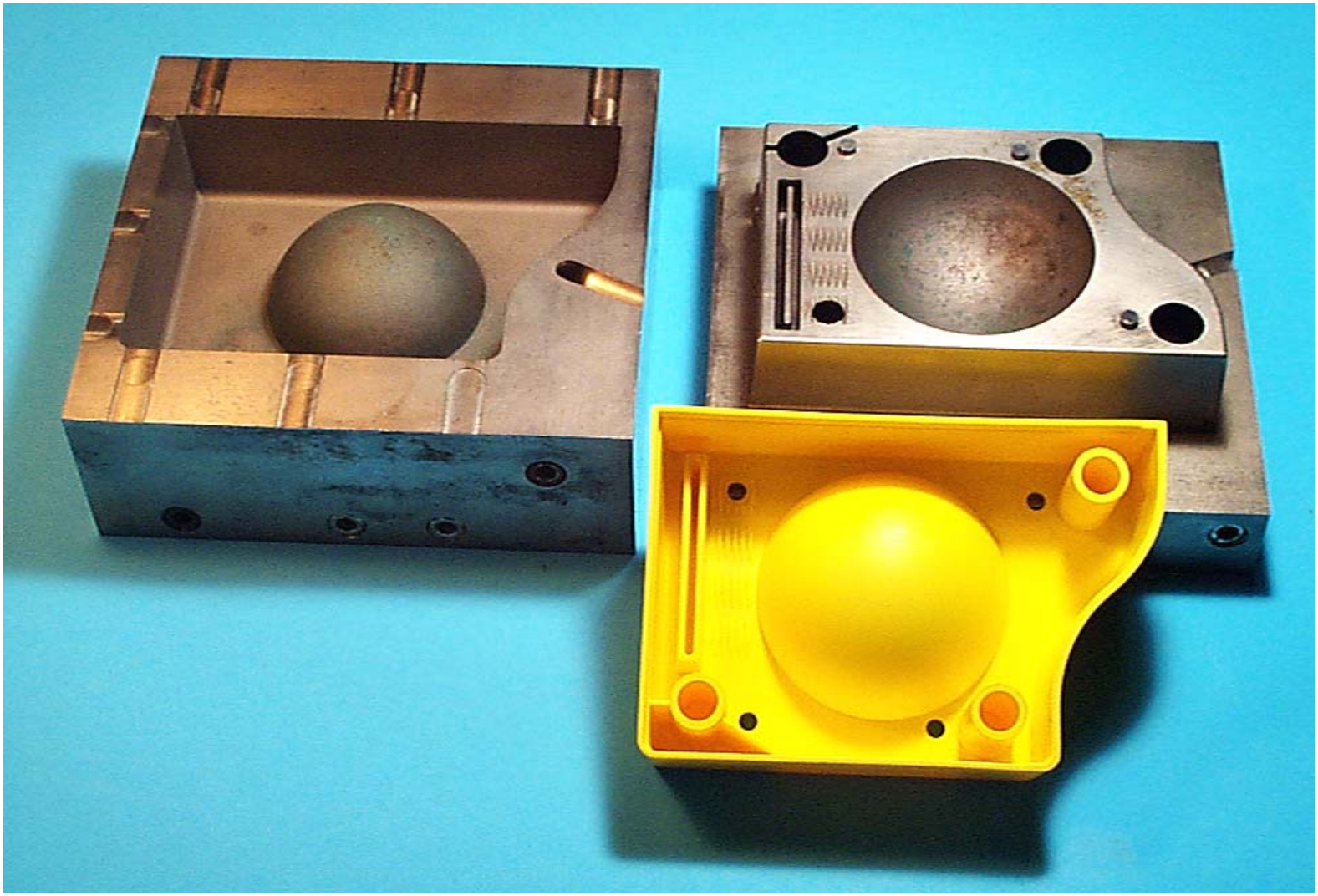
Green part
58% metal
10% polymer
32% open porosity

→ Debind by thermal decomposition & pre-sinter to 63% dense →

Infiltrate to full density with copper alloy →

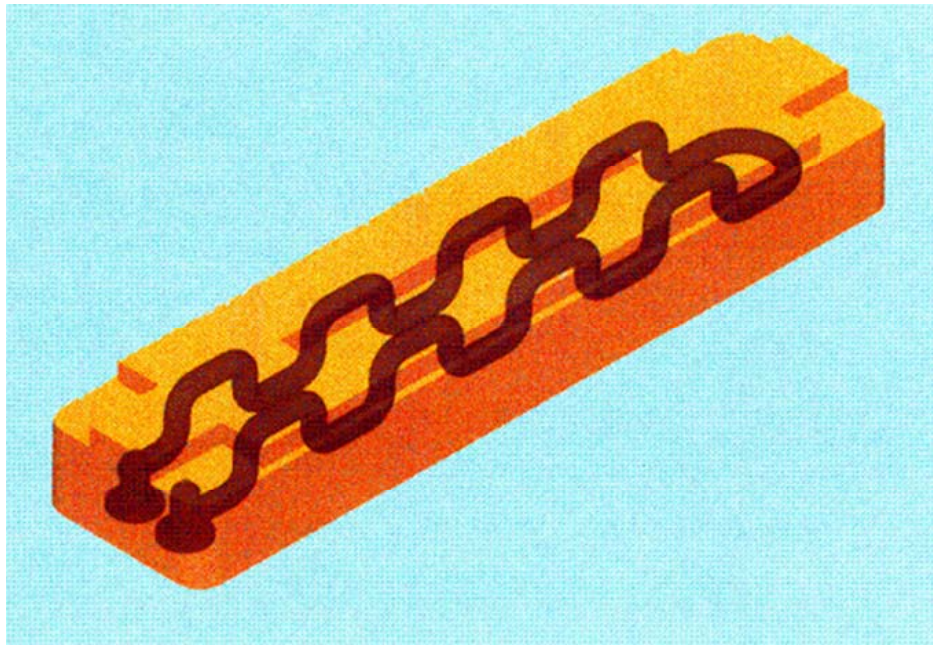
Finish → Tool Insert

Finished Tool and Molded Part



Conformal Cooling in an Industrial Application

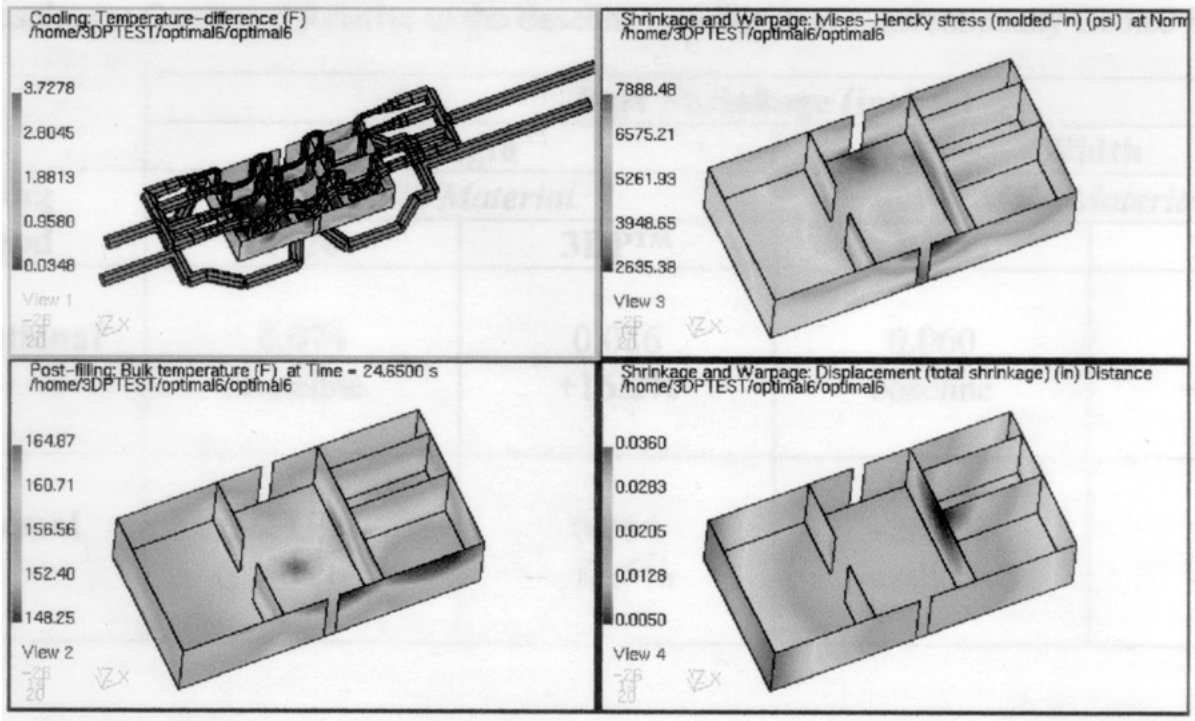
Tool made by 3D Printing with serpentine cooling channel



Improvement over Production Tool

	Cycle time	Part Distortion
Condition #1	**15%(limited by sprue)**	**9%**
Condition #2	**0%(limited by sprue)**	**37%**

Conformal Cooling; Data from Design of Expt's



- **Typically**
  - **20% reduction in cycle time**
  - **15% reduction in shrinkage**

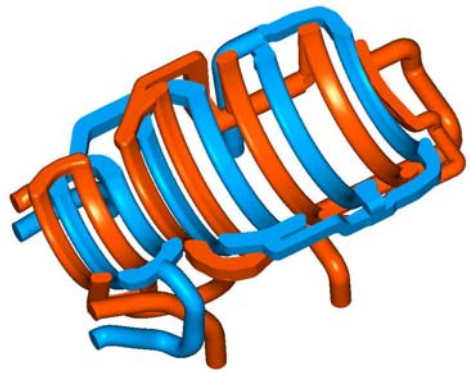
Schmidt et al, "Conformal Cooling vs Conventional Cooling: An Injection Molding Case Study with p-20 and 3DP tooling, MRS 4/00

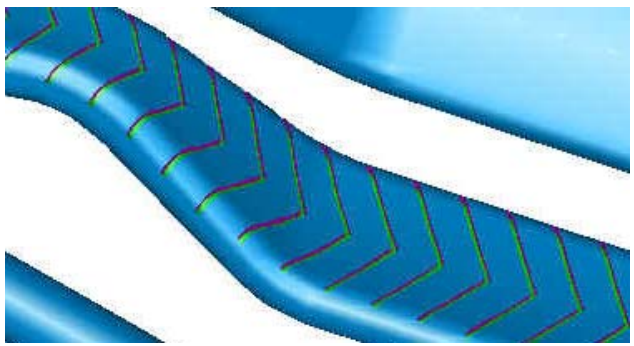
Partnership in Technology

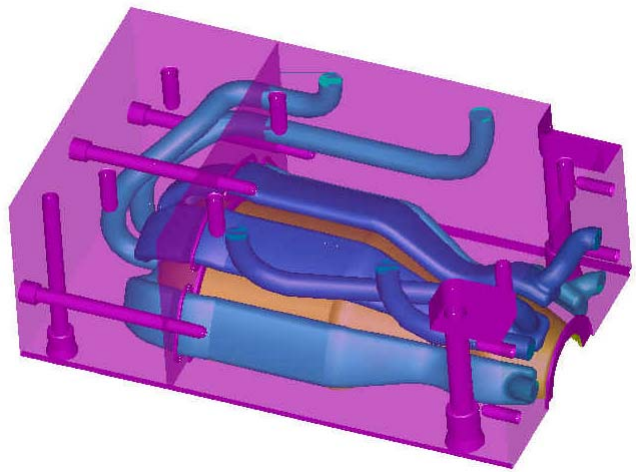
EXTRUDEHONE™

D-M-E

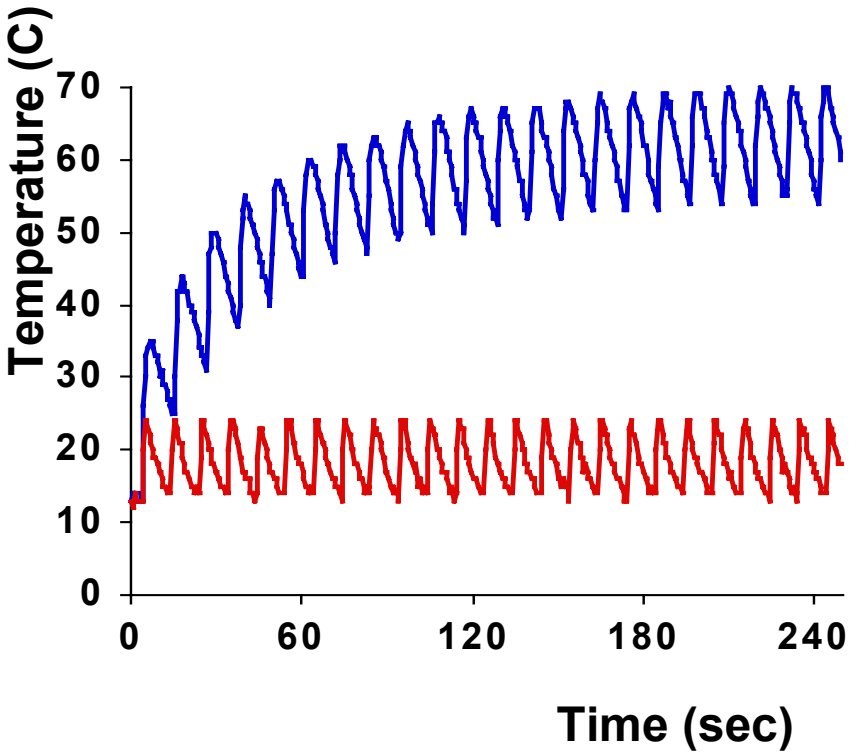
- **Blow Mold Cavities**
  - ***MoldFusion*™ First Design**
    - Two conformal and opposing flow circuits
  - ***MoldFusion*™ Second Design**
    - Two conformal linear flow circuits
    - Turbulence chevron features

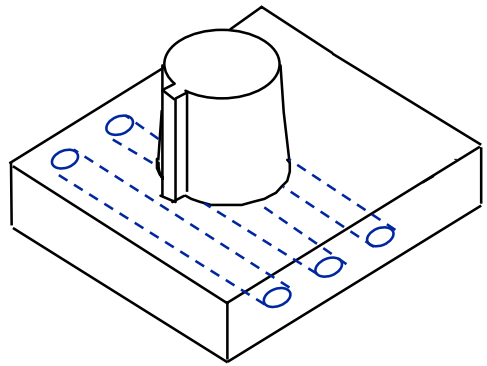


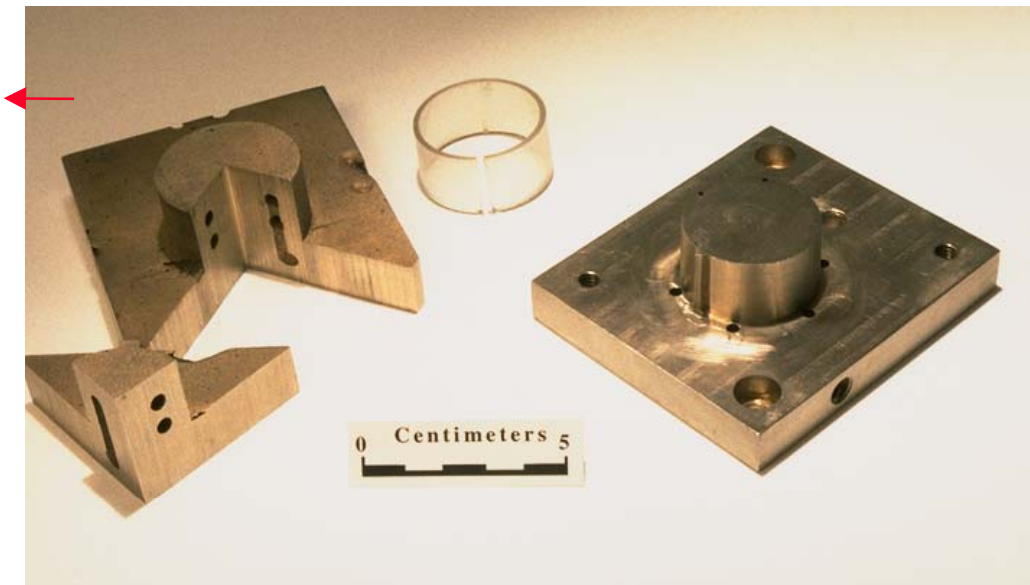




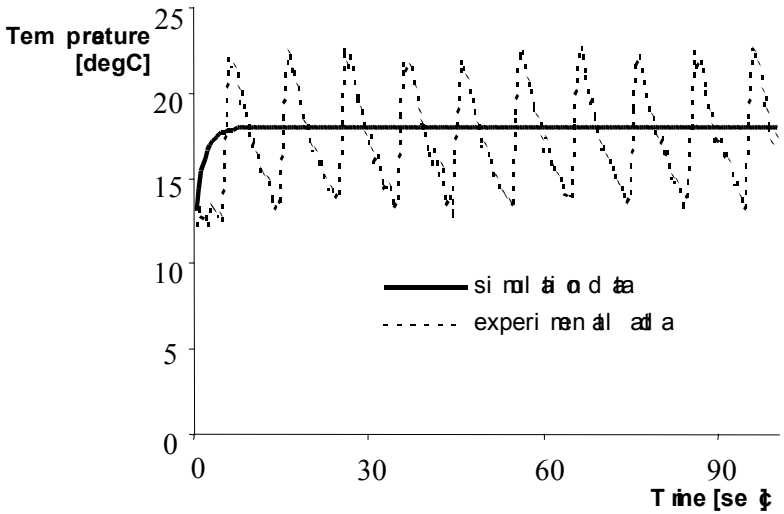
Demonstration of Performance:Conformal Cooling

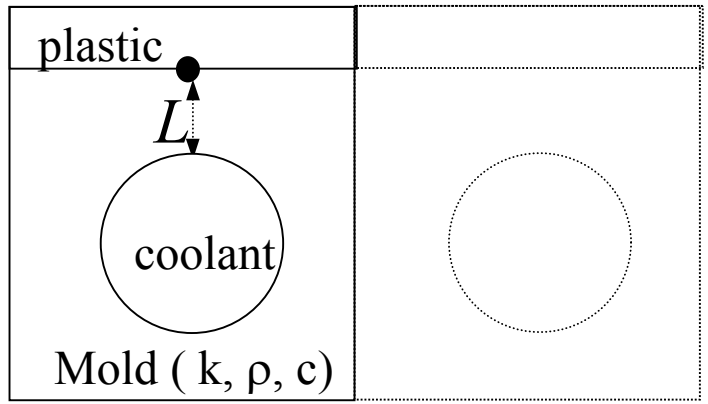






Conformal Cooling Condition



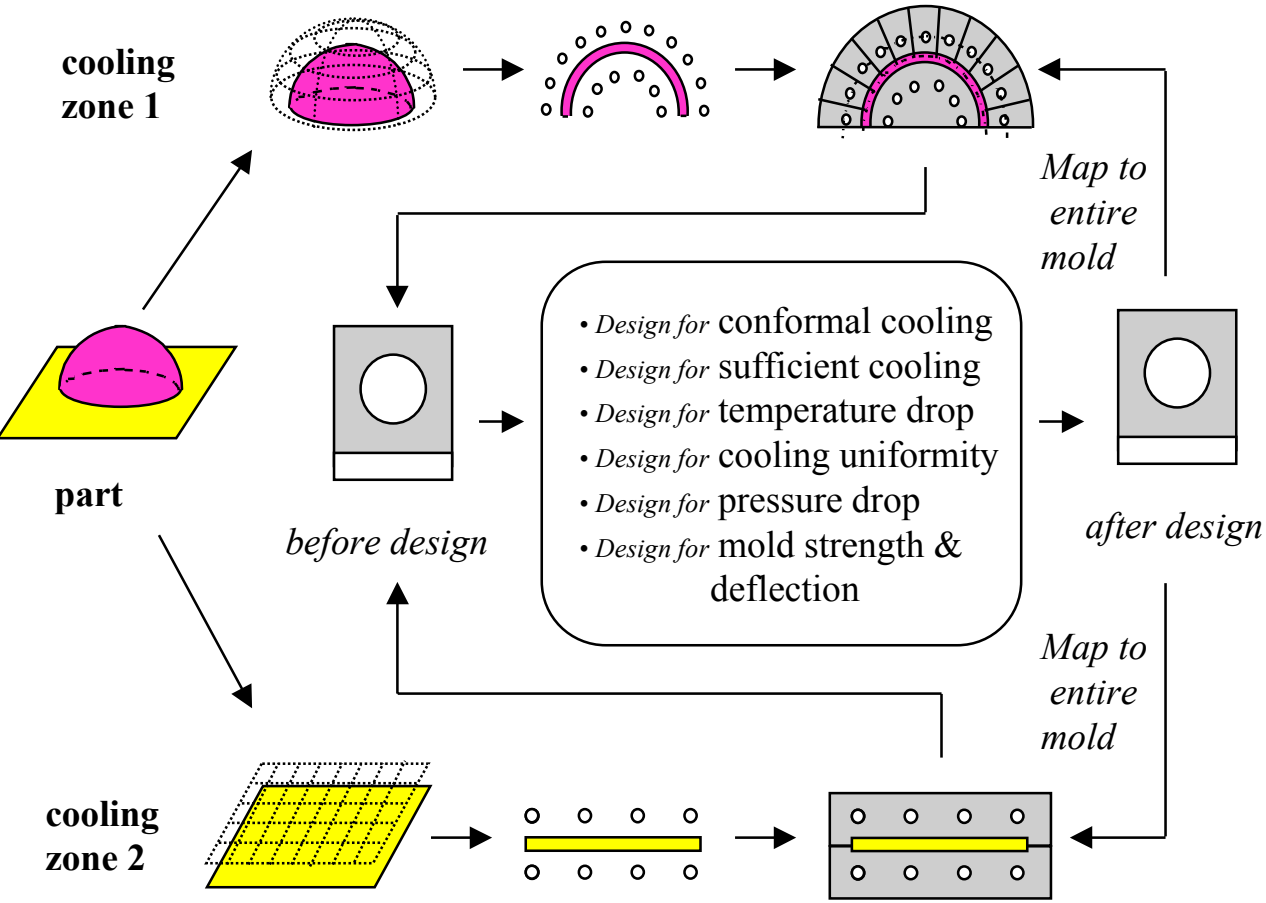


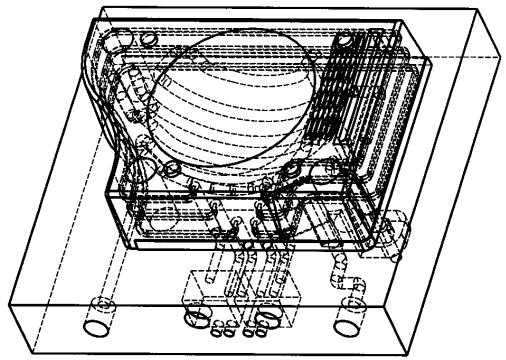
One cooling cell

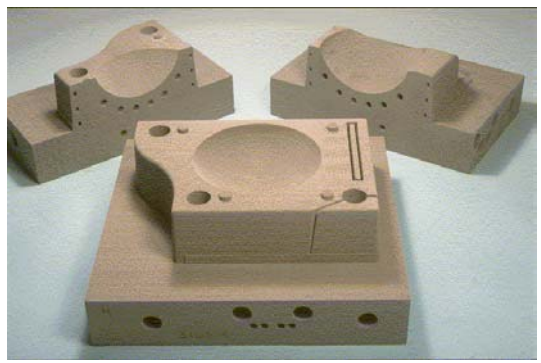
Adjacent cooling cell

$$\frac{L^2}{k} < \frac{\text{Cycle Time}}{\rho\, c}$$

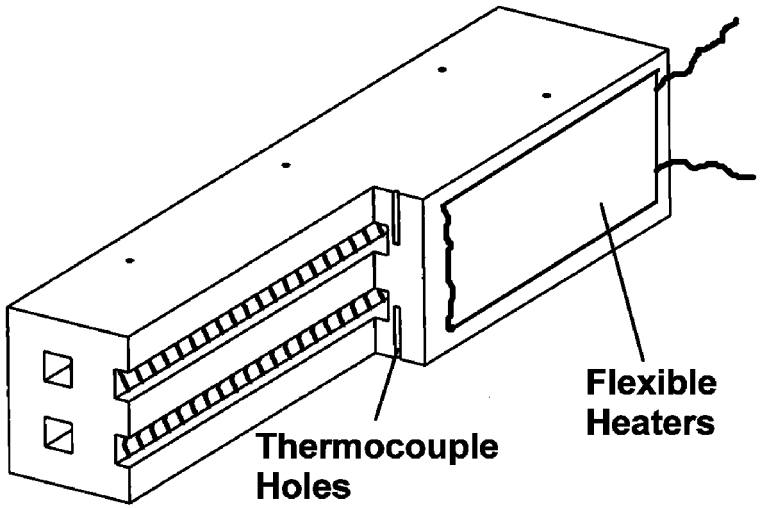
Conformal Cooling Channel Design Methodology

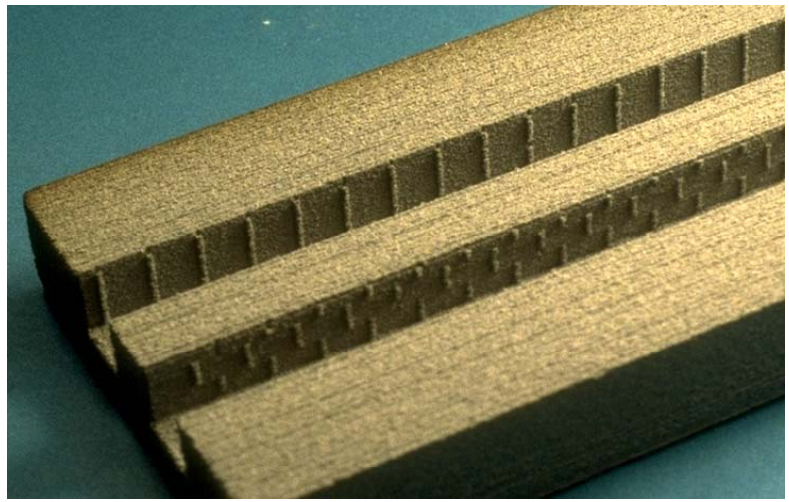


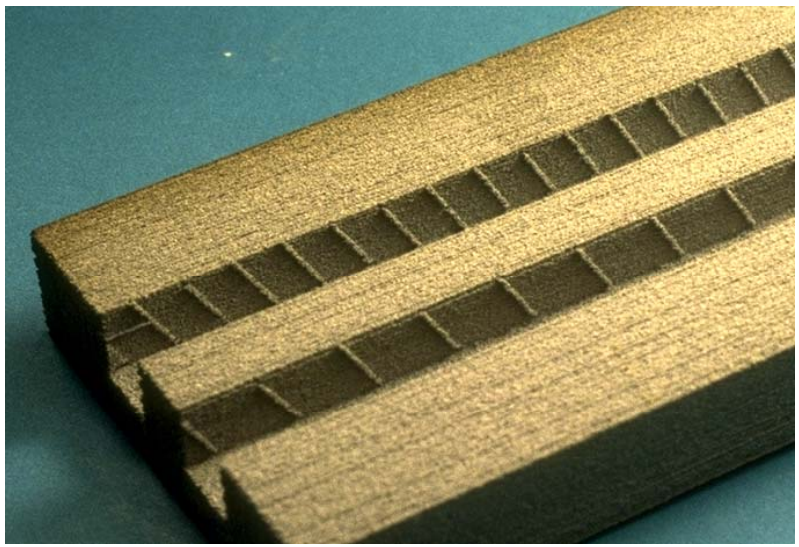


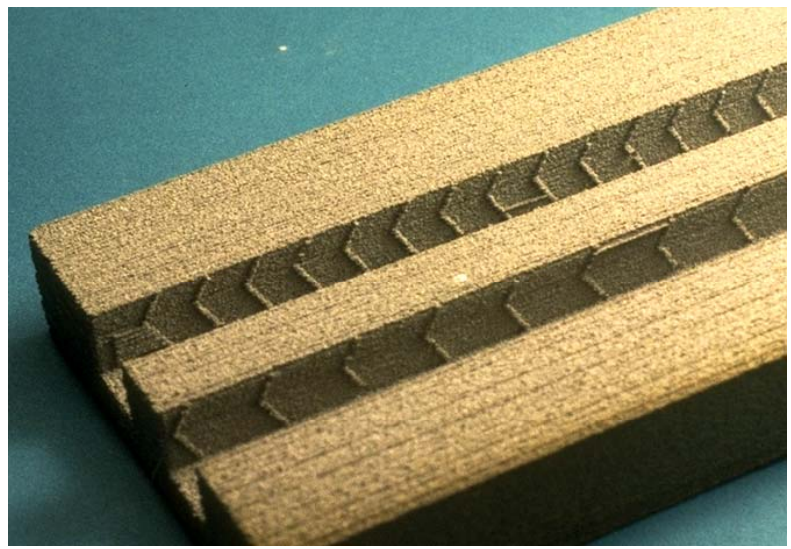


Surface Textures for Heat Transfer Augmentation

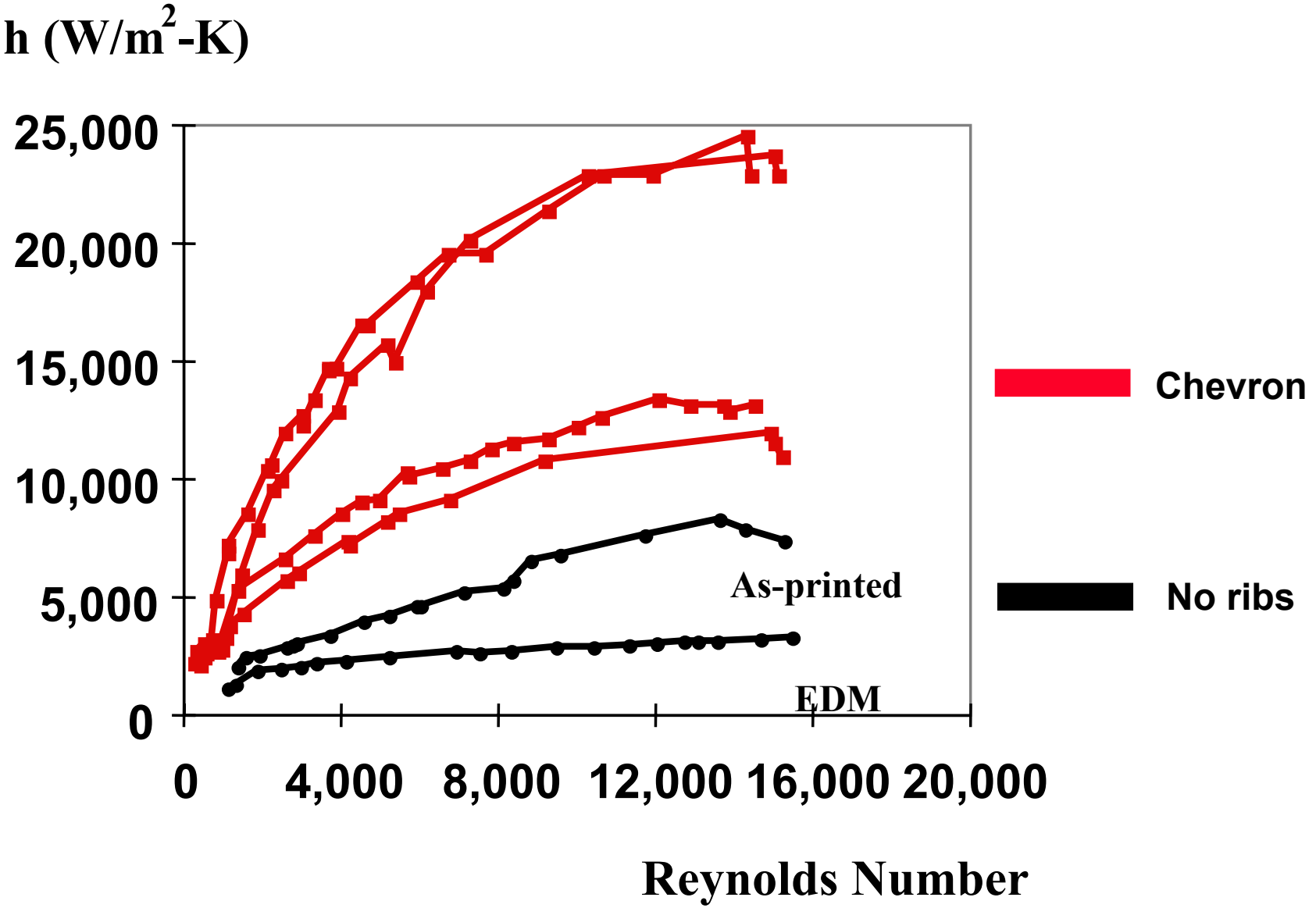




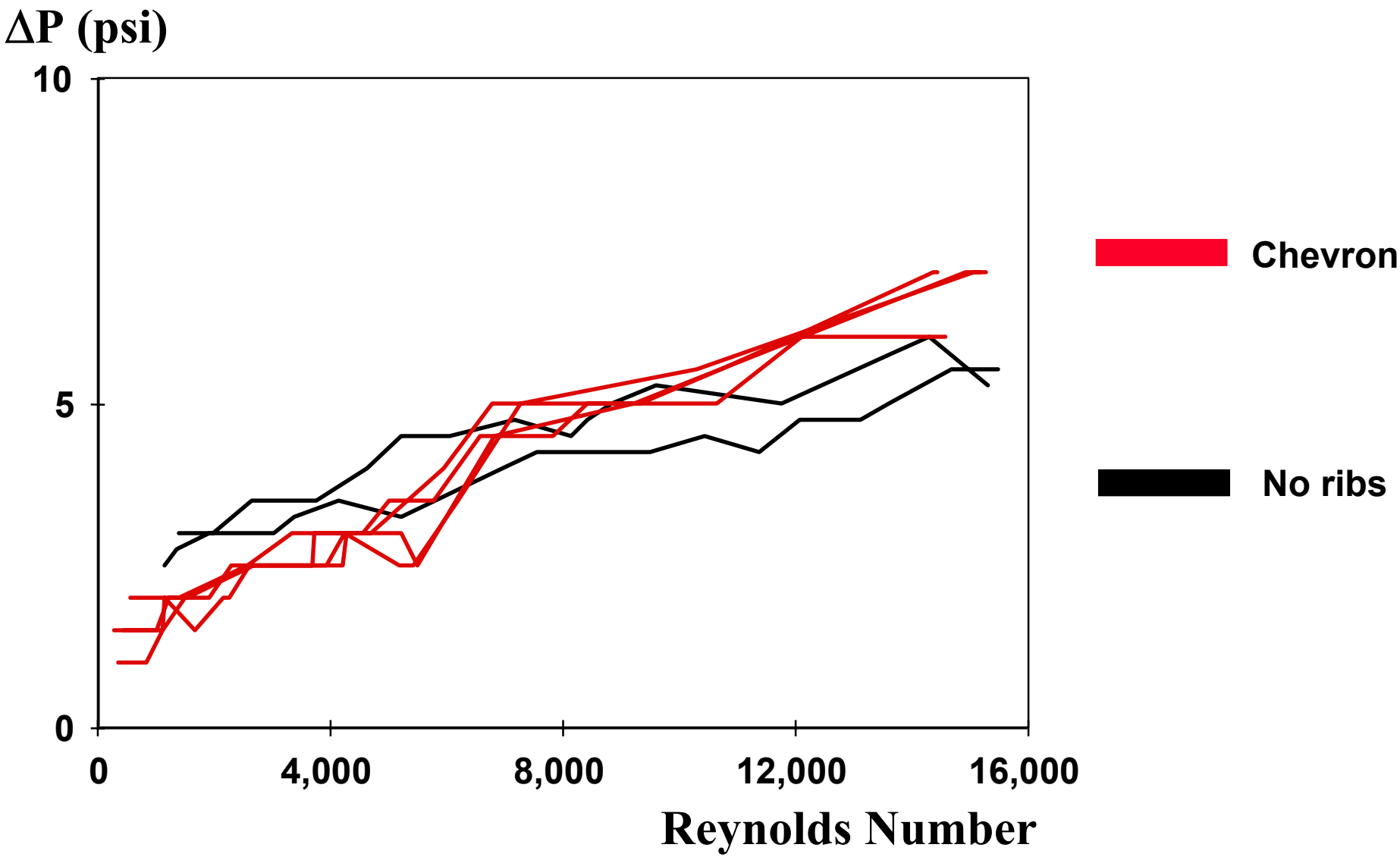




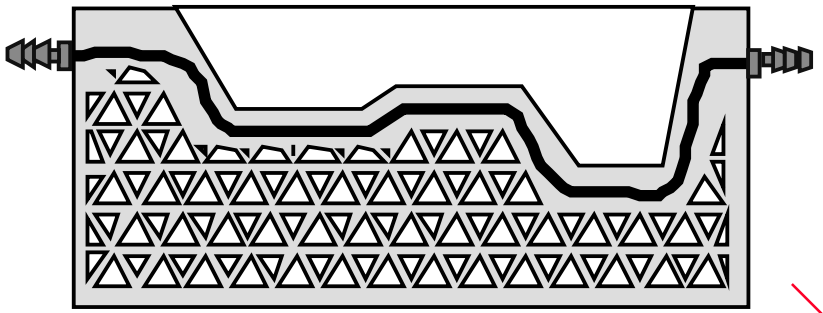
Heat Transfer Coefficient



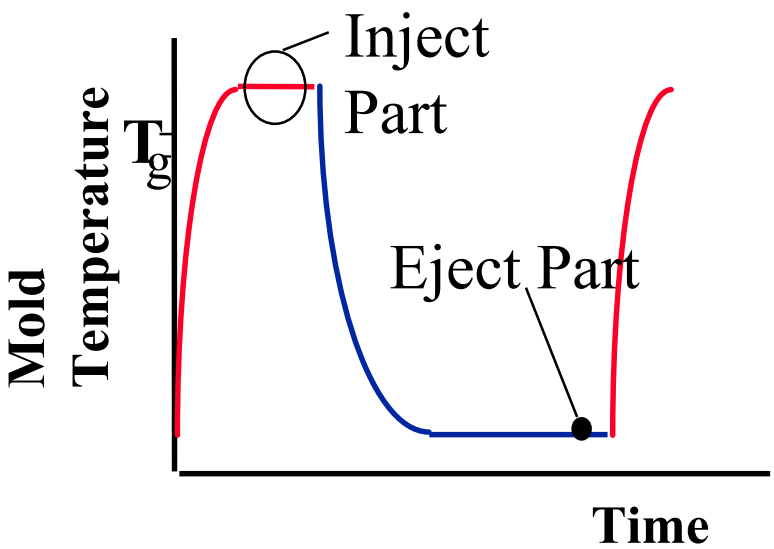
Pressure Drop (ΔP)



Rapid Thermal Cycle Tooling

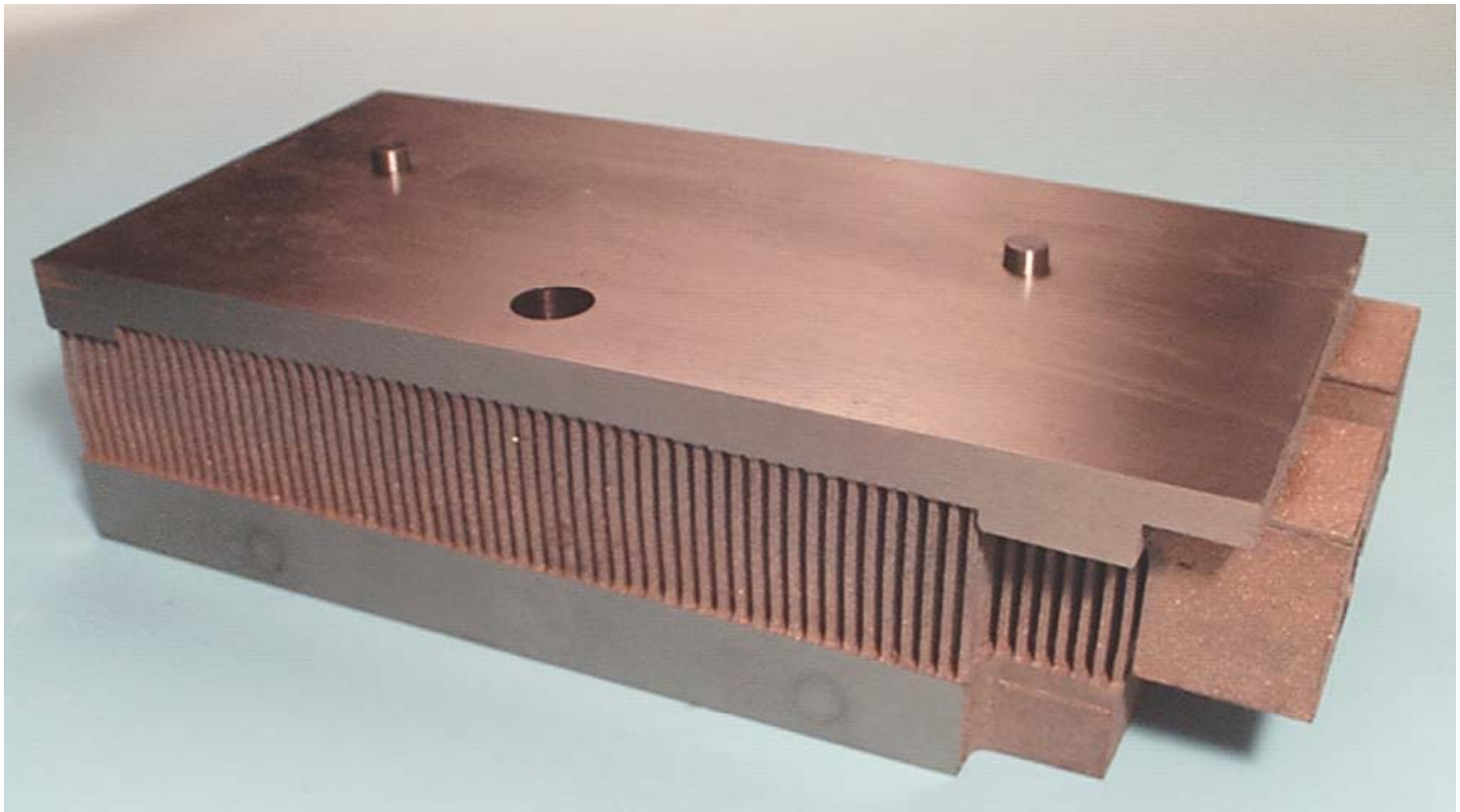


Constant Temperature



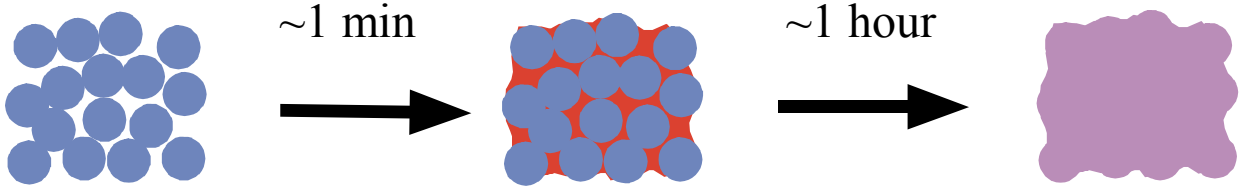
Cycled Temperature

3D Printed Tool for Rapid Thermal Cycling



The tool has cooling/heating channels in the top plate and stands on 2000 posts (which allow for thermal expansion/contraction)

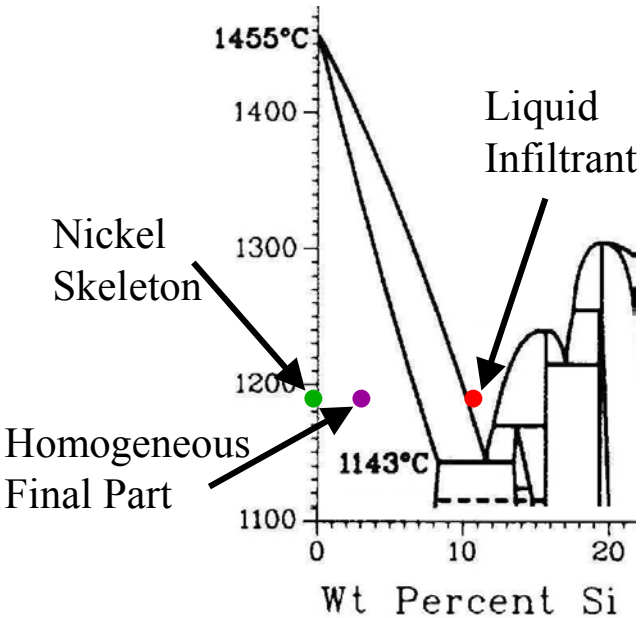
Homogeneous Metal Parts by Infiltration



Porous skeleton of nickel or other high temperature material

Infiltration using same material containing a melting point depressant (MPD)

Diffusion of MPD into skeleton creates a solid homogeneous part



~1 kg infiltrated part (Ni–4Si)

Infiltration Distance

- **Capillary limit**

$$h = \frac{1}{\rho g} \cdot \frac{2\gamma}{r}$$

>0.5 m typical for 100 μm powder

- **Premature freezing of infiltrant can choke liquid flow**

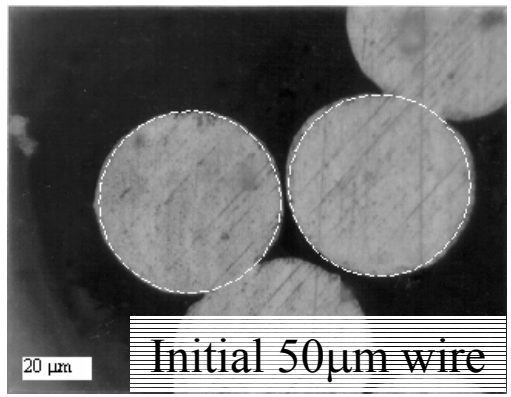
Skeleton made of ~ 50–150 μm powder (both cases)

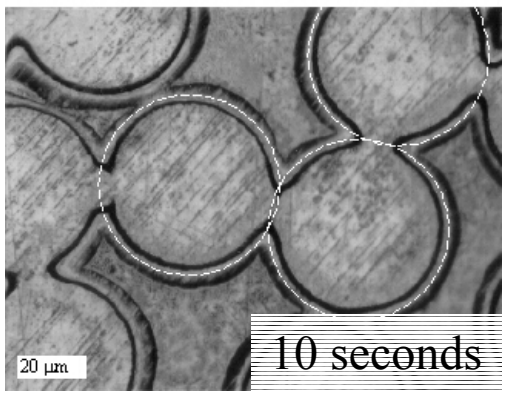
Ni infiltrated with Ni-10Si

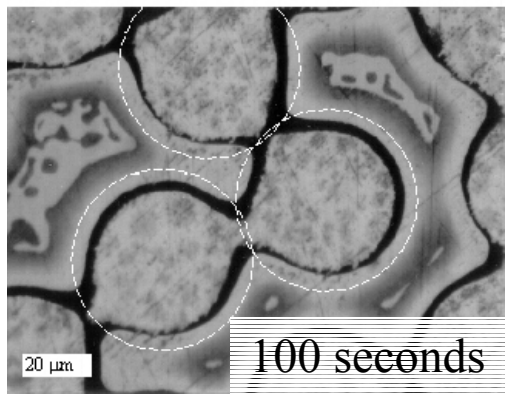
Steel infiltrated with Cu

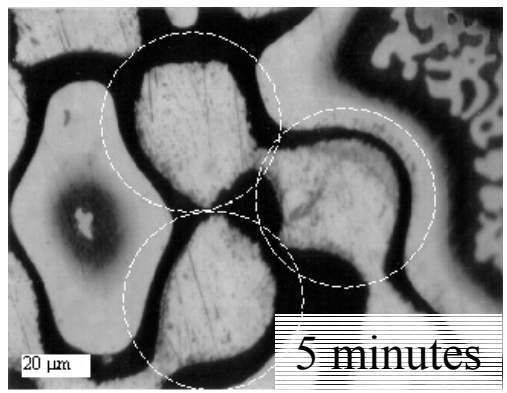
Solidification Time Sequence

- **Wire bundle infiltrated and quenched at various times**
- **Ni wire w/ Ni–10Si infiltrant**
- **Infiltrated at 1200°C**









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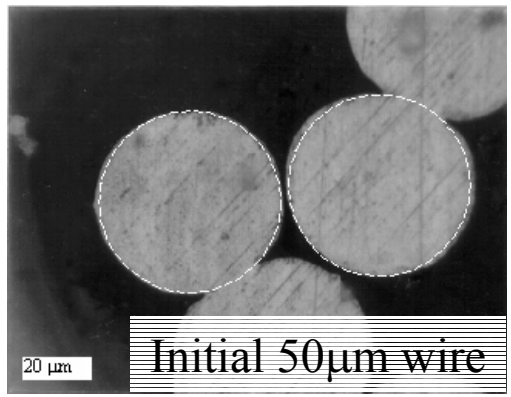
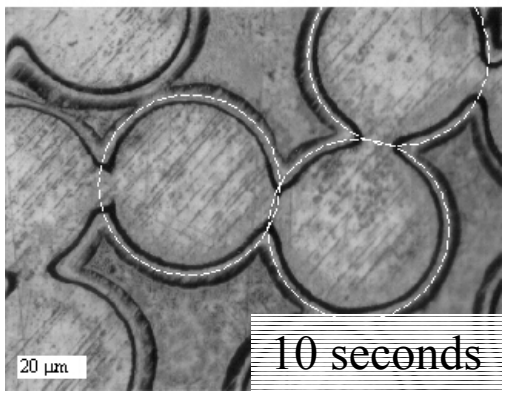
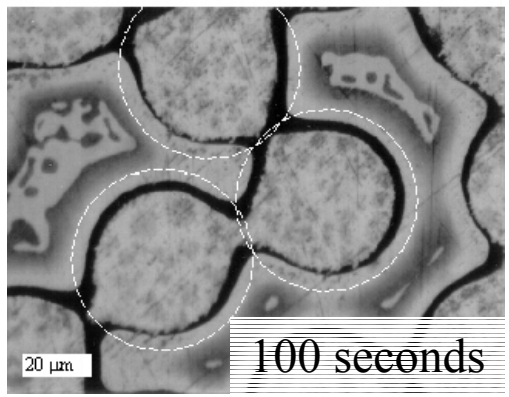
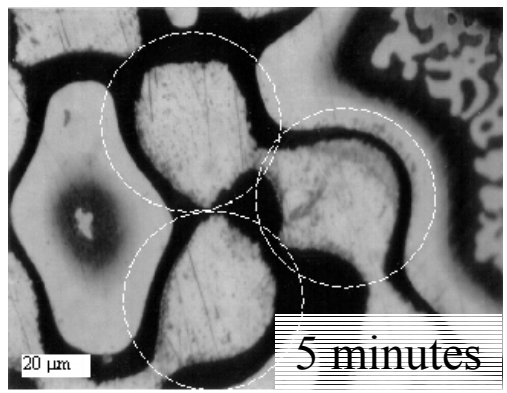


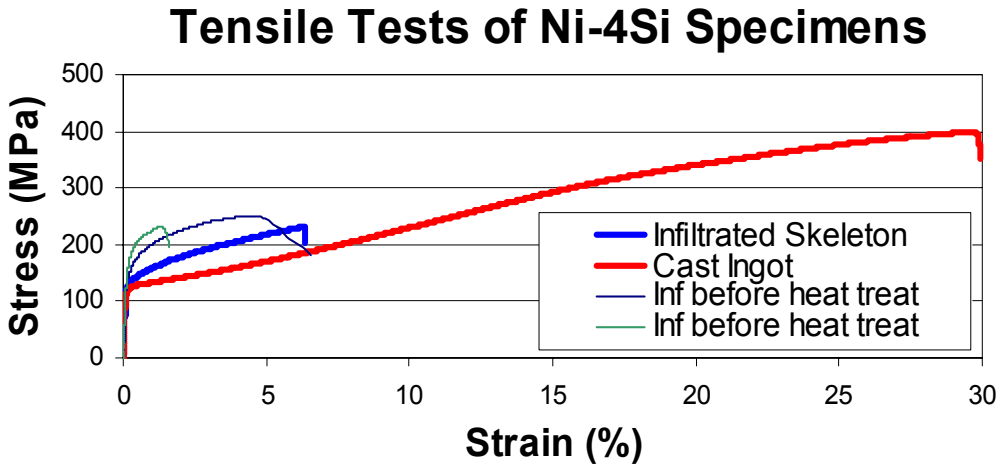






Mechanical Properties

Infiltrated

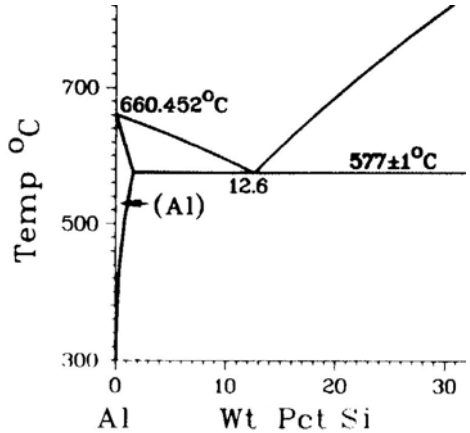


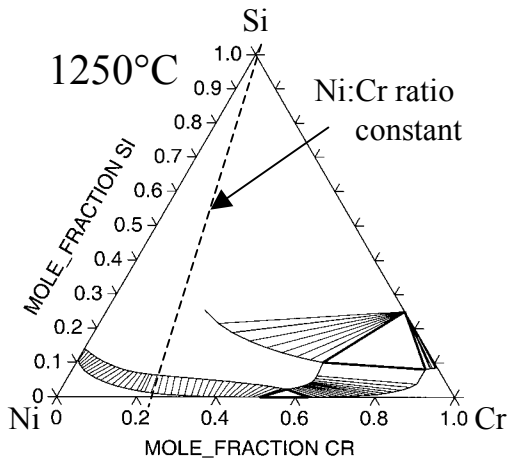
- **Infiltrated skeleton held 12 hrs at 1200°C for homogenization**
- **Cast ingot of same composition**
- **Hopefully Cr or other elements will provide more strengthening**

Cast ingot

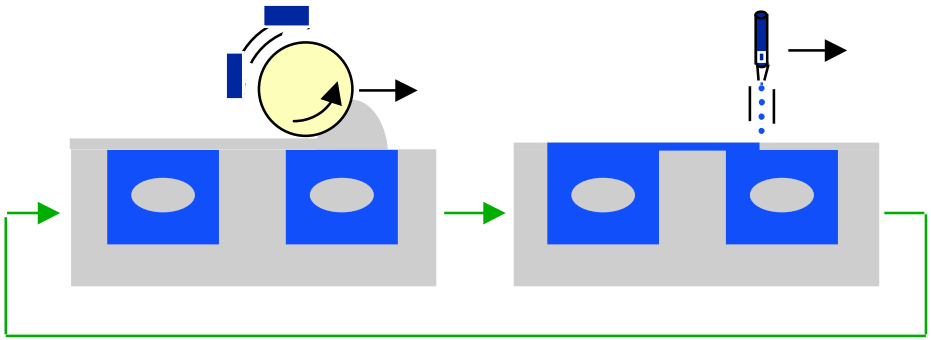
Other Material Systems

- **Al–Si**
  - **Low solubility (no freeze-off)**
  - **Similar to cast microstructure**
  - **Pure Al infiltrated w/ Al–12Si at 625°C achieved 93.5% density**
- **Ni–Cr–Si**
  - **solid solution strengthening**
  - **keep constant Ni:Cr ratio during diffusional solidification**
- **Steel?**



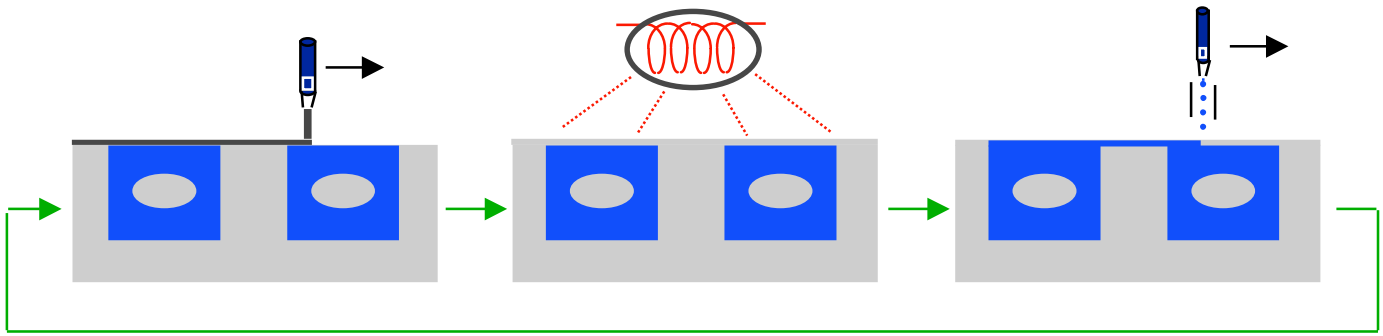


3D Printing: Dry vs. Wet Layer Spreading



Dry

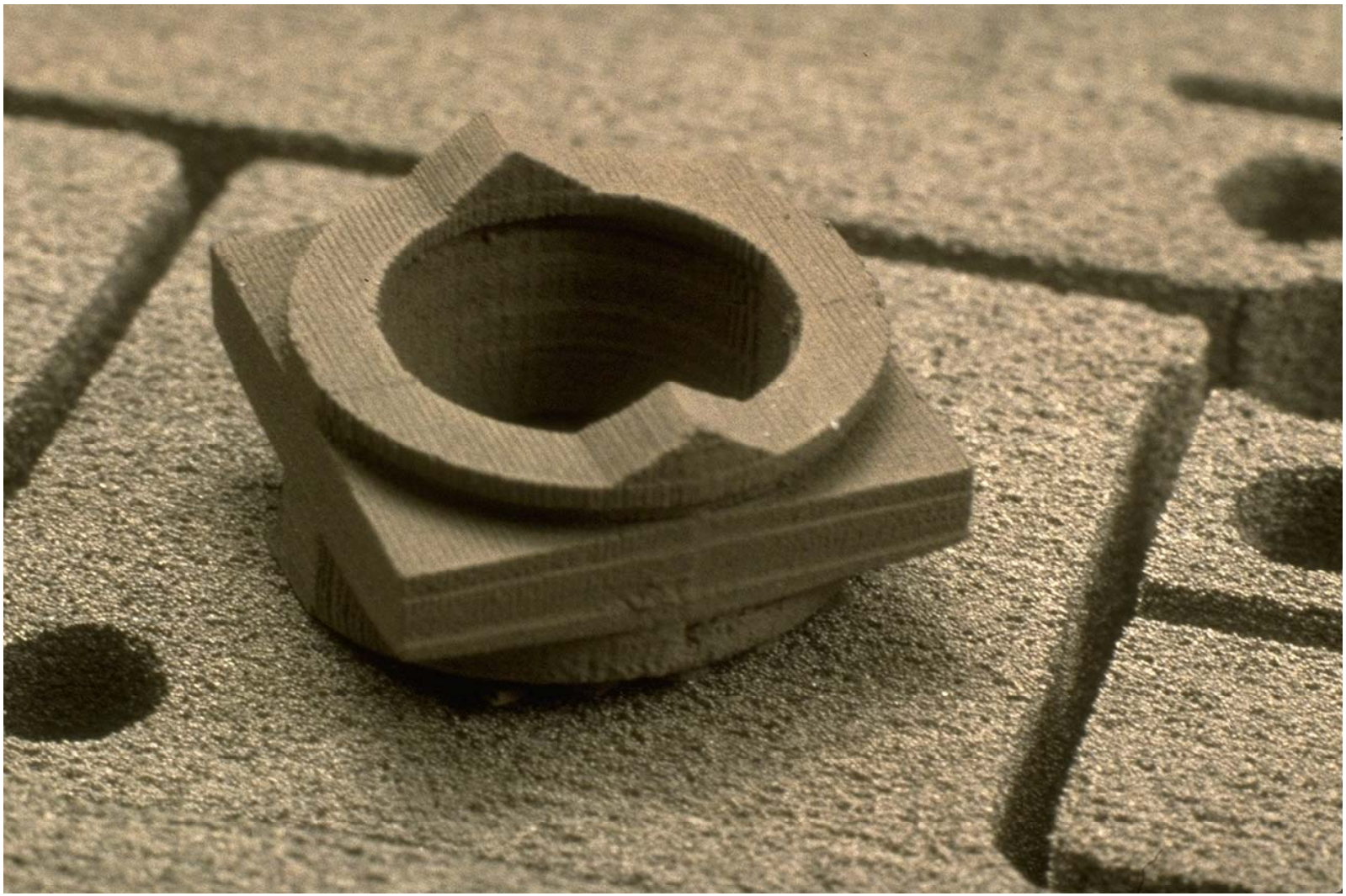
- **Spherical as small as 10 μ**
- **Acycular as small as 20 μ**



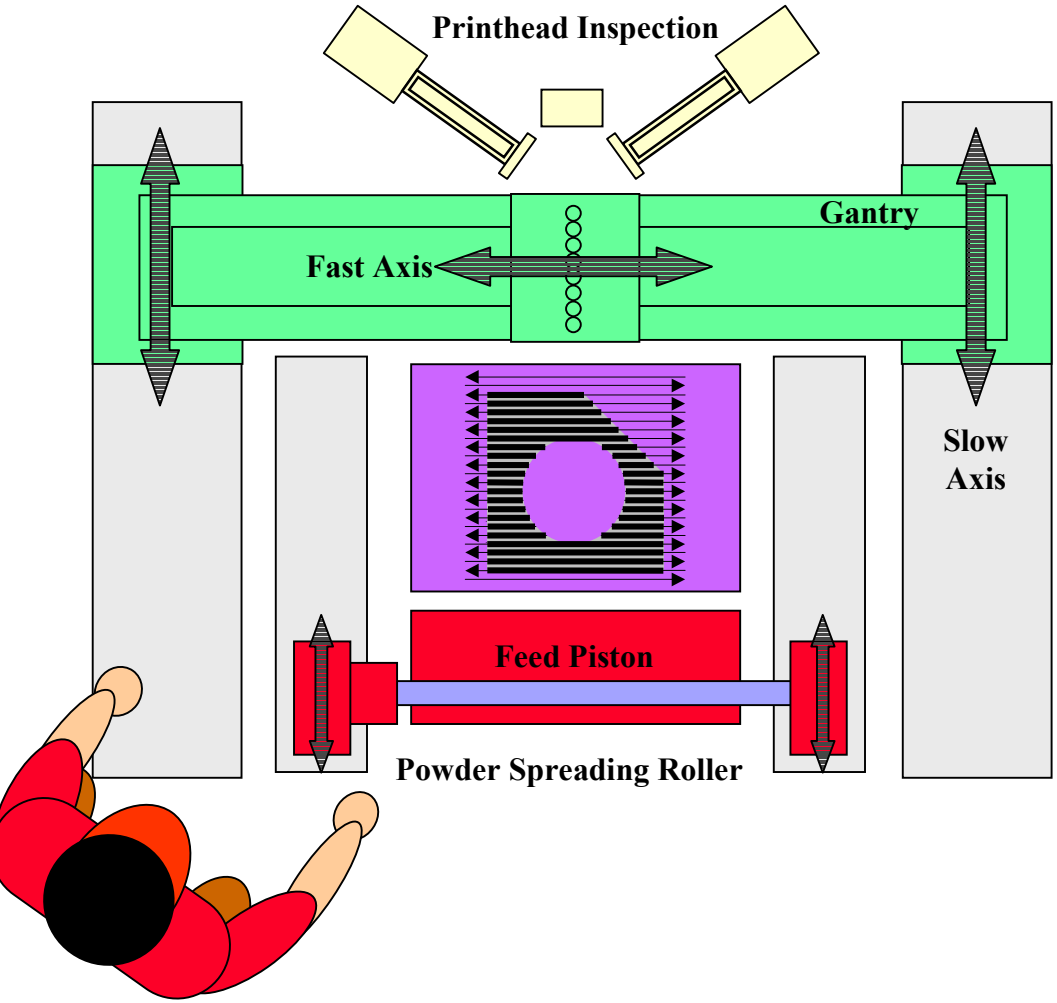
Wet

- **Anything that can be slurry processed**

Parts with Fine Metal Powder



Architecture 1: Stationary Bed, Raster Print

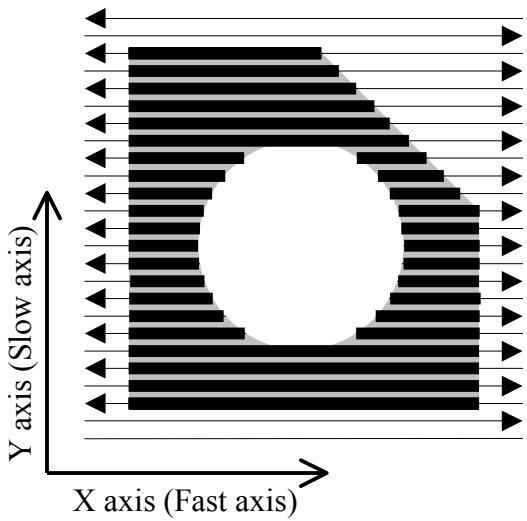


Z Corp.

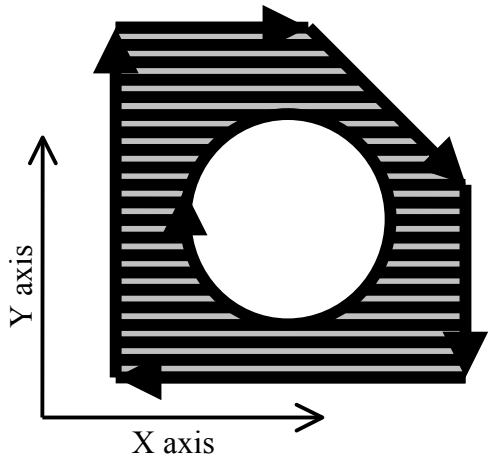
ExtrudeHone Corp.

Small Parts; Distinguishing Features

- **Powder beds are small , light (<1 kg) and often cohesive.**
  - ⇒ **Move powder bed**
- **Perimeter is short**
  - ⇒ **Vector Print the perimeter.**

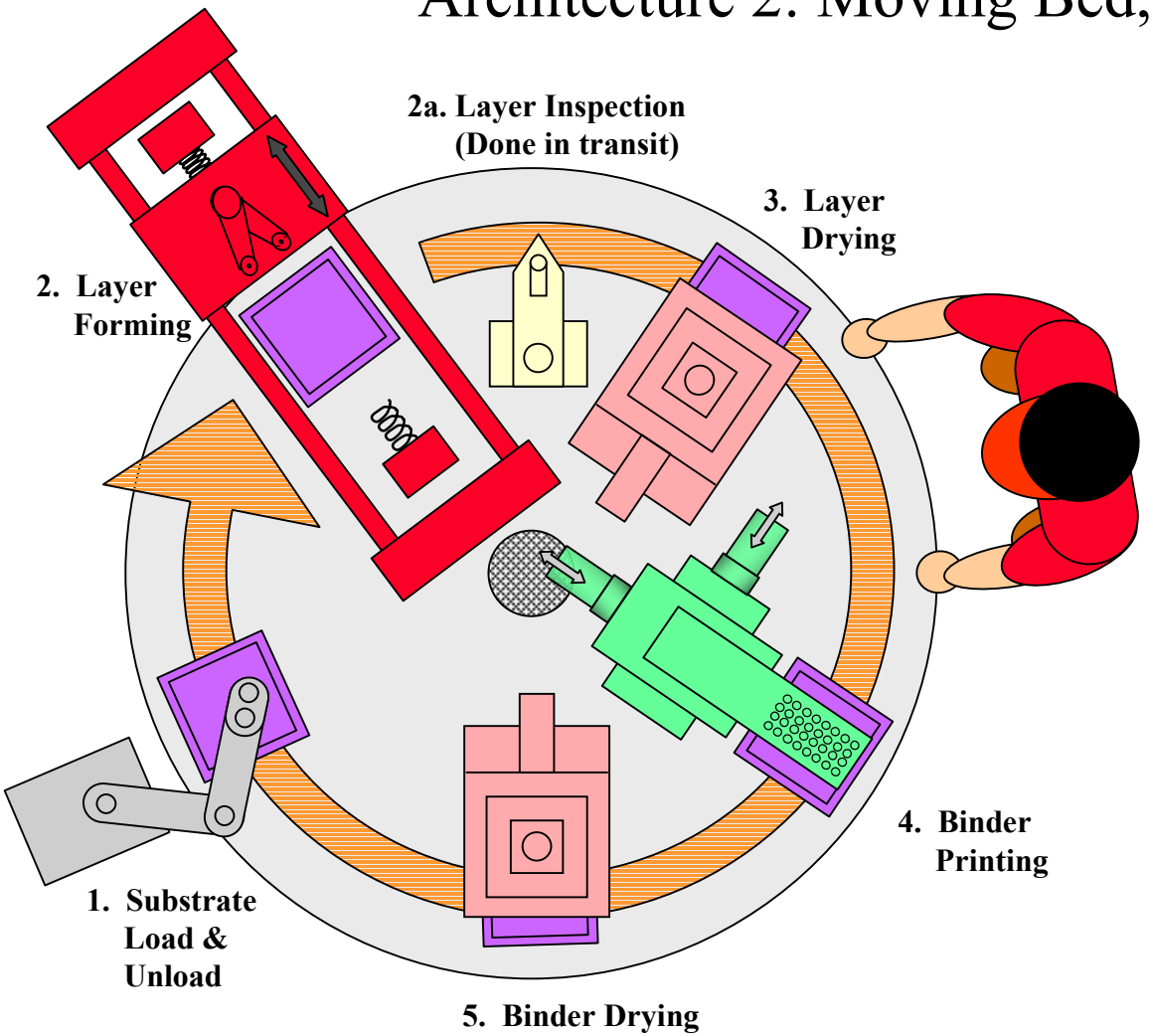


Raster printing



Vector printing

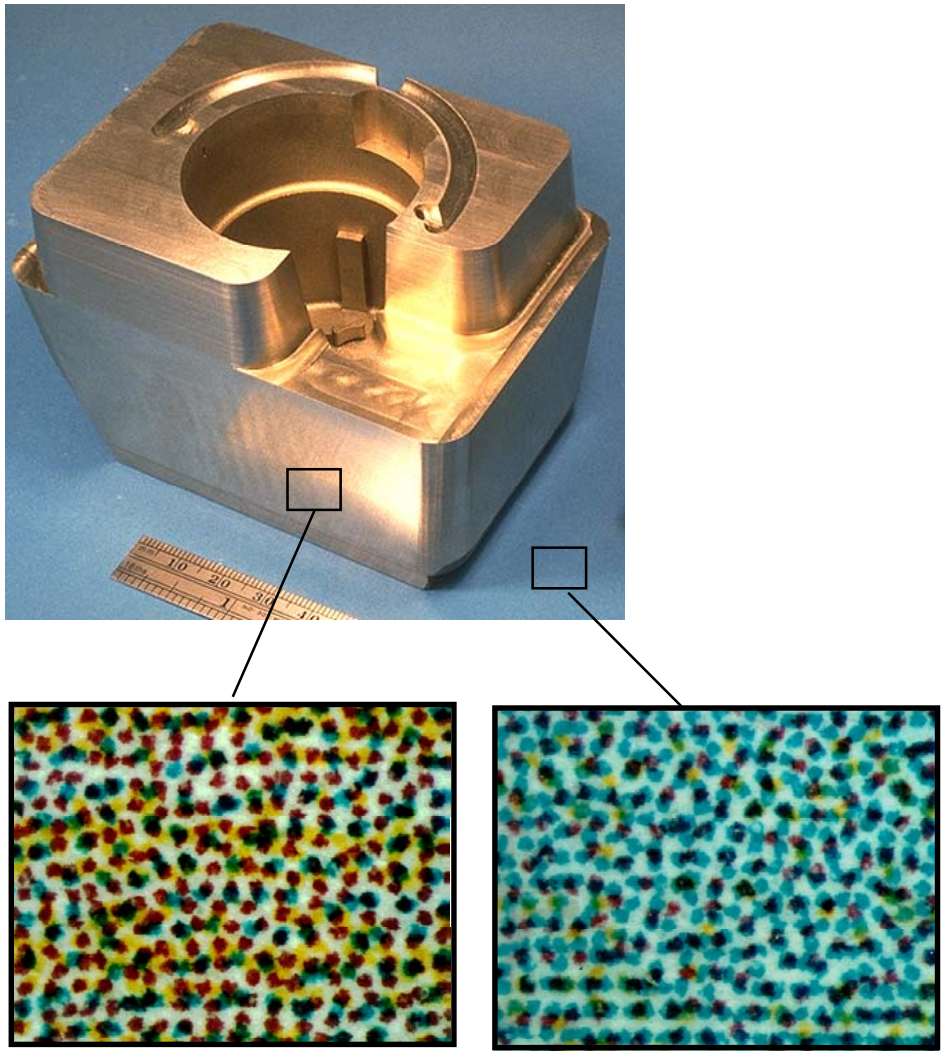
Architecture 2: Moving Bed, Vector Print

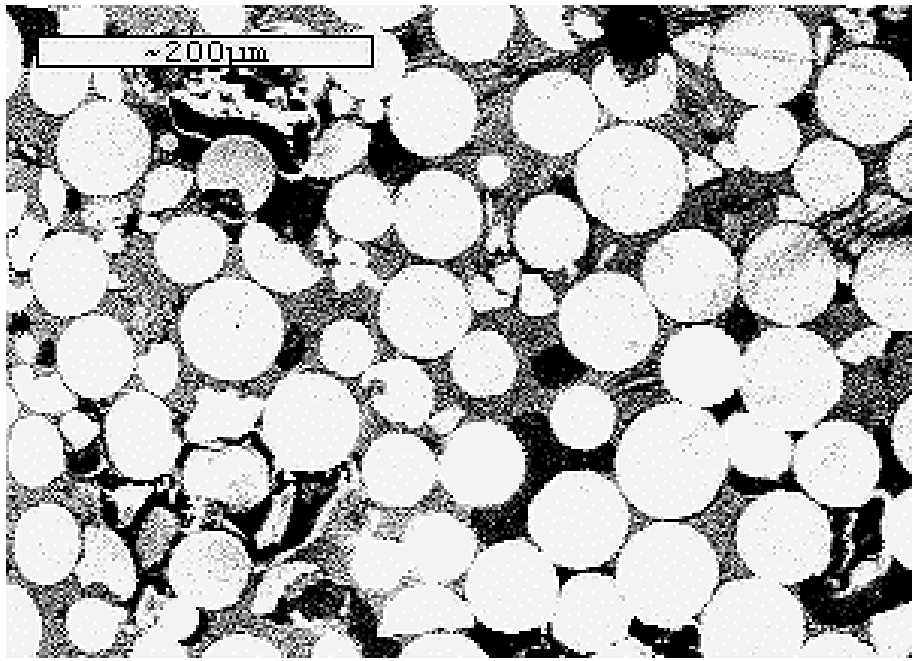


- **All stations in use all the time.**
- **Automation ready.**
- **Improved surface finish.**

Barrium Titanate Parts made by 3DP with Slurry

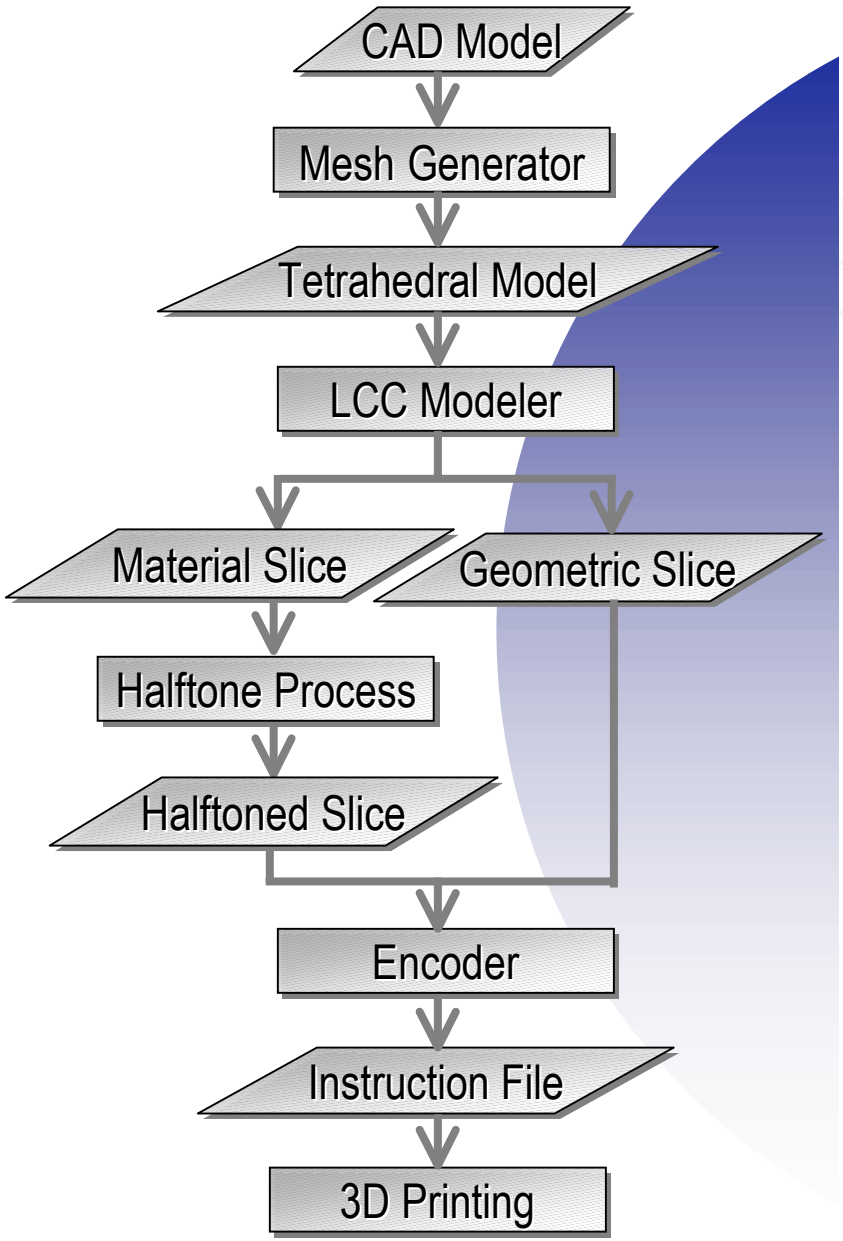
Local Composition Control; Like Color ink-jet Printing, but with Materials

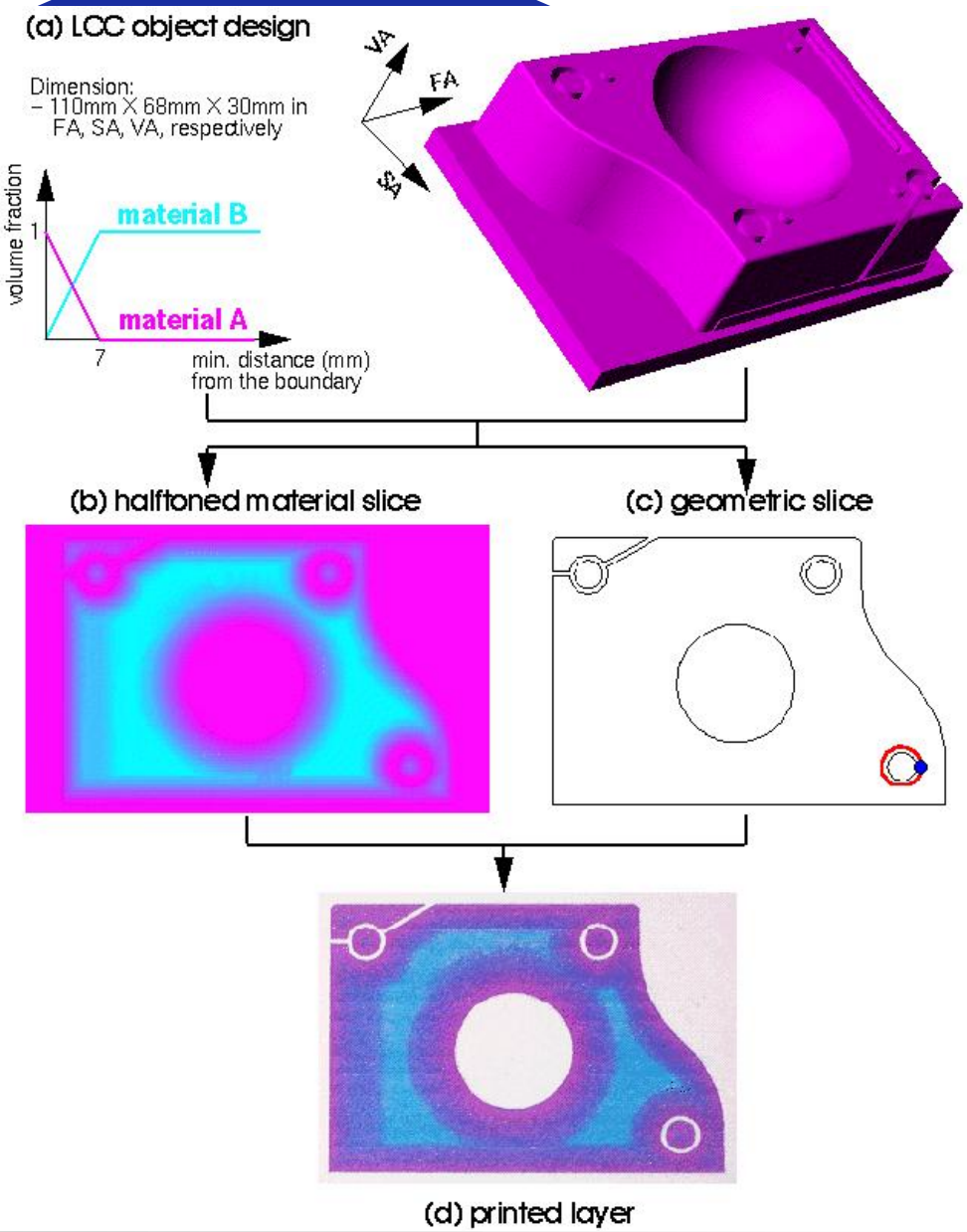




Titanium Carbide slurry printed in Moly powder; 83% dense

Information Flow





Summary:
3DP for Thermal Management

- **Cooling/heating channels - high complexity**
- **Surface textures**
- **Macro cellular structures**
- **Locally controlled porosity**
- **Locally controlled thermal conductivity**